A Review on Reducing the Impacts of Urbanisation through Greener Approaches

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Abstract

It is well known that urbanisation has a notable effect on the hydrologic and environmental dynamics of a catchment. The purpose of this paper is to present a brief review on the effects of urbanisation and compare the various approaches taken to minimise these impacts. Urbanisation has been identified to intensify the response of a watershed, increasing the magnitude of storm peak flow, by up to a factor of 12 and reducing post-development lag time to less than half that of the pre-developed state. Large watersheds were found to be less sensitive to urbanisation due to channel transmission losses. Urban catchments are characterised by a lack of infiltration, hence the 'first flush' of accumulated pollutants is mobilized to the catchment outlet, rather than retained, increasing the magnitude and frequency of pollutant wash-off. In order to respond to post development effects of urbanisation, implementation of greener approaches such as permeable pavement and bio retention systems are encouraged, as well as the implementation of rainwater tanks. Moreover, the concurrent implementation of on-site detention and Water Sensitive Urban Design (WSUD) systems has been found to effectively replicate the response of a natural catchment to a large degree. Overall, this paper acknowledges that whilst on-site detention is necessary to reduce the excessive peak flows of urban catchments, the simultaneous implementation of greener approaches would better mimic natural catchment dynamics.

***Keywords*: WSUD, Permeable pavement, Bio retention, Urban water cycle, Urban flood**

1. INTRODUCTION

Urbanisation results in an increase of impervious area, the establishment of man-made drainage systems and alteration of land topography (Codner, Laurenson and Mein 1988). Due to hydraulic modifications, catchments experience an increase in peak flows, a decrease in lag time and in turn, amplified susceptibility to flooding (Endreny et al 2005). In the early 1990's, on-site detention (OSD) systems were rapidly adopted by Sydney Councils to counteract the effects of urbanisation on catchment hydrology (O'Loughlin et al 1995). Urban areas are also predisposed to increased sources of contamination, such as motor vehicles, sewage and general refuse (Ferreira et al 2016). Stormwater runoff from urban areas accumulate nutrients such as nitrogen and phosphorous, as well as hydrocarbon toxins (Bannerman et al 1993). The high pollutant concentration of urban runoff has the potential to adversely affect downstream environments. Greener processes such as water sensitive urban design (WSUD) devices have been implemented within the majority of Sydney Councils, in order to reduce the impact of development on water quality. This paper reviews a number of technical papers to assess the effectiveness of WSUD systems, particularly bio-retention and permeable pavement systems, in urban stormwater management.

2. IMPACT OF URBANISATION ON WATER QUALITY

Increasing catchment imperviousness has been found to result in a reduction of infiltration and an increase of storm runoff (Ferreira et al 2016, Yang et al 2011). Urban runoff contains high concentrations of sediment and nutrients (Brattebo 2003, Elliot 2009, Gilbert et al 2006). An investigation by Codner, Laurenson, and Mein (1988) identified that the urban Giralang catchment recorded a 50% higher average concentration of nitrate, ammonia and orthophosphate than the rural Gungahlin catchment. This result is supported by Tasdighi et al (2017) who identified that even seemingly minimal increases in urban land use (5-10%) can increase vulnerability to nitrogen and phosphorous by up to 50%. Due to the increased magnitude of runoff and increased concentration of contaminants, the total mass of pollutants discharged from urban areas is far greater than pollutant export from rural catchments.

Between storm events, pollutants settle on the surface of a catchment. During a storm event, the majority of accumulated pollutants are mobilized to the catchment outlet by the first flush of runoff. The first flush of a storm event is defined by Li-qing et al (2007), as being the initial 30% of runoff volume. The results of Li-qing et al (2007) identified that the first flush contained 62.4% of TSS, 46.8% of TN and 54.1% of TP. Due to the high pollutant concentration of the first flush, peak pollutant discharge occurred earlier than the peak stormwater discharge.

As rural catchments are predisposed to infiltration and evapotranspiration, the first flush of settled pollutants is absorbed rather than discharged, resulting in higher quality runoff (Codner et al 1988). Conversely, urban areas are characterised by impervious area and generate higher runoff volumes. This leads to the discharge of almost all settled pollutants through the catchment drainage system, a decrease in water quality and the potential collapse of healthy downstream aquatic ecosystems (Roy et al 2007).

3. GREENER APPROACH

The employment of WSUD should serve to restore and replicate the critical stages of a natural catchment's hydrologic and environmental response, protect downstream ecosystems and increase the sustainability of development (Roy et al 2007, Stuart et al 2010). In order to enhance sustainable development, bio-retention and porous pavement systems are encouraged (Hunt et al 2006, Alsubih et al 2017).

A bio-retention basin is a stormwater quality improvement device which utilizes natural processes such as filtration, biological uptake and evapotranspiration to clean stormwater (Trowsdale and Simcock 2011). Bio-retention basins comprise of shrubs planted within a sand and soil media. Stormwater is filtered through the sand and soil, and nutrients are removed through biological processes (Hunt et al 2006). Water infiltrates into agricultural pipes and is connected into the downstream drainage system.

The efficiency of a bio retention basin is dependent on basin size, antecedent soil conditions, the grade of soil media, storm intensity and basin age (Hunt et al 2006). By monitoring three bio-retention systems over the course of a year and completing a statistical analysis, Stuart (2010) identified that whilst results for each storm event varied greatly, the average annual retention capacity was 18%. The results of Trowsdale and Simcock (2011) and Hunt et al (2006) displayed in Table 1 confirmed that the magnitude of retention was subject to storm intensity and typically ranged between 6%-64%.

Table 1. Bio retention Capabilities (Stuart 2010, Trowsdale and Simcock 2011, Hunt et al 2006)

Study	Average Stormwater Retention (%)
Stuart 2010	18
Trowsdale and Simcock (2011)	6-64
Hunt et al (2006)	7-54

The results of Trowsdale and Simcock (2011) displayed that the analysed bio retention system was especially effective at reducing TSS and zinc concentrations, however increased the dissolved copper concentration of runoff. Similarly, Hunt et al (2006) identified that the three monitored bio retention devices, on average increased pollutant concentrations for TKN and TP. Pollutant reductions from an array of studies were summarised in Table 2.

Table 2. Pollutant concentration reduction by bio retention systems

Reference	TSS (%)	TKN (%)	TP (%)	Cu (%)	Zn (%)
Dietz and Clausen (2006)	-	26	-108	-	-
Davis et al (2003)	-	52	65	97	95
Davis et al (2003)	-	67	87	43	64
Rossen et al (2006)	96	-	-	-	99
Hunt et al (2006)	-170	-5	-240	99	98
Hunt et al (2006)	-	45	65	-	-
Trowsdale and Simcock (2011)	90	-	-	-50	95

It was suggested by Dietz (2007) that the increase of phosphorous concentrations may be due to the bio retention soil having a high phosphorous index, or due to the decomposition of organic litter and mulch. Whilst certain studies identify that under certain conditions bio retention systems are capable of increasing pollutant concentrations, the general trend indicated that bio retention systems greatly improve stormwater quality. The results stress the importance of regular monitoring and system maintenance to ensure functionality (Hunt et al 2006).

The infiltration capacity of permeable pavement depends on the particle size distribution of the bedding material and the antecedent moisture conditions (Scholz et al 2007, Alsubih et al 2017). Several investigations have been conducted to measure the infiltration capacity of permeable pavement. Through a case study of 6 watersheds, Gilbert et al (1996) identified that whilst asphalt pavement experienced no infiltration, the UNI EcoStone Permeable Interlocking Concrete Pavers (PICP) achieved an average infiltration rate of approximately 11.8 cm/h. The results were displayed in Table 3. The values obtained by Gilbert agree with those of Brattebo (2003), who concluded that the UNI Ecostone pavement, produced no runoff from an average storm intensity of 5.2 cm/h.

Table 3. Infiltration rates of Asphalt and Permeable Pavement (Gilbert et al 2006)

Test and Year	Asphalt (cm/h)	Permeable Paver (UNI EcoStone) (cm/h)
Single Ring infiltrometer (2002)	0	11.8 ± 9.5
Single Ring infiltrometer (2003)	0	10.5 ± 5.9
Flowing (2003)	0	11.4

Through evaluation of a 3200m^2 stretch of highway, Pagotto et al (2000) identified that implementation of porous asphalt (PA) doubled the catchment response time. Several studies verified that the implementation of PA delayed runoff initiation and reduced peak discharge, therefore increasing catchment response time (Alsibuh et al 2017, Prat et al 1995, Pagotto et al 2000).

Through laboratory testing of a 1m^2 sample of Prioro block permeable pavement (PICP), Alsubih et al (2017) identified that porous pavement attenuated peak flows and delayed runoff. It was identified that dry antecedent moisture condition resulted in an increase of stormwater retention and a greater delay of runoff initiation. Furthermore, as the magnitude of gross rainfall increased, the proportion of retained runoff decreased. These findings were illustrated in Figure 1. Alsubih et al (2017) concluded that within all 41 simulated rain events, the PICP pavement retained more than 40% of incident rainfall.

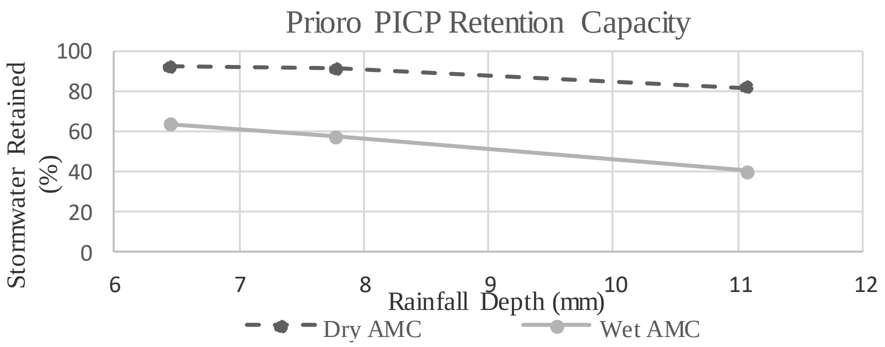

Figure 1. PCIP Retention Capacity (Alsibuh et al 2017)

Within numerous studies, the implementation of permeable pavement was linked to significant reductions of TSS, TKN, TP, copper and zinc pollutant export. The results achieved by Gilbert and Clausen (2006), Pagotto et al (2000) and Brabetto et al (2003) were summarised in Table 4 and Table 5.

Table 4. Total pollutant export of asphalt and permeable pavement (Gilbert et al 2006)

	Asphalt (kg/ha/year)	Permeable Pavement (UNI EcoStone) (kg/ha/year)	Reduction in Pollutant loads (%)
Total Suspended Solids (TSS)	230.1	23.1	90
Total Kjeldahl Nitrogen (TKN)	13.06	1.08	91.7

Table 5. Total pollutant concentration of asphalt and permeable pavement (Brabetto et al 2003)

	Asphalt (μg/l)	Permeable Pavement (UNI EcoStone) (μg/l)	Reduction in Pollutant loads (%)
Copper (Cu)	7.98	0.86	84
Zinc (Zn)	21.6	6.8	68.5

The results of Brabetto et al (2003) and Pagotto et al (2000) affirmed that the implementation of permeable pavement resulted in a significant reduction of pollutants from runoff. Brabetto et al (2003) demonstrated that 84% of copper and 68.5% of zinc were removed due to implementation of porous pavement, whilst Pagotto et al (2000) achieved copper and zinc removal efficiencies of 34% and 66% respectively. A comparison of the achieved results identified the consistent values of zinc removal efficiency, whilst demonstrating the irregularity of copper removal data.

Permeable pavement has great capacity for the removal of oils and hydrocarbons from stormwater runoff. Numerous case studies have acknowledged that no hydrocarbons were detected from permeable pavement runoff (Booth et al 1999, Scholz et al 2007, Brabetto et al 2003). This common finding was disproven by Pagotto et al (2000) who identified that implementation of permeable pavement within a highway road surface reduced hydrocarbon concentration by 92%.

4. CONCLUSION

Urbanisation is found to increase runoff magnitude, decrease catchment response time, increase runoff frequency and increase pollutant export. The efficiency of bio retention basins has been found to vary subject to basin size, age, soil properties and antecedent moisture condition. Bio retention basins are found to result in 6%-64% retention of runoff and large reductions of TSS, TKN and TP. The requirement of regular monitoring and maintenance has been emphasized as numerous studies have revealed that neglected systems increase pollutant concentrations. Nevertheless, when maintained, bio retention systems effectively assist in replicating the natural processes of rural catchments, reducing both the magnitude of runoff and pollutant wash off.

The implementation of porous pavement systems within urban catchments has been found to yield a significant reduction of runoff volume and an increase of catchment response time. Additionally, porous pavement has been found to greatly reduce the concentrations of TSS, TKN, TP and hydrocarbons in the urban runoff.

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